Pulse Power Performance of the Cygnus 1 and 2 Radiographic Sources

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Abstract

Cygnus is a two-axis radiographic x-ray facility designed to drive rod-pinch diode loads at 2.25 MV with a spot size of about 1 mm producing 4 Rads at 1 meter. This x-ray source was developed to support the Sub-Critical Experiments Program (SCE) at the Nevada Test Site (NTS) and is distinguished from other commercially available sources by a dramatically reduced spot size for high resolution radiography, higher reliability, and compact size and modularity for greater layout flexibility to fit within the size constraints of its ultimate underground site location [1]. The facility is composed of two virtually identical machines referred to as Cygnus 1 and Cygnus 2 that incorporate proven pulsed power technology. Each machine employs a Marx generator, Pulse Forming Line (pfl), Water Coax Transmission Line, and Inductive Voltage Adder (IVA) that drive a high vacuum rod-pinch diode. The pfl design was originally developed for the Radiographic Integrated Test stand (RITS) [2] and the IVA cells are from the Sandia SABRE [3] accelerator. The Cygnus 1 machine was constructed and fielded at the Los Alamos National Laboratory to undergo pulsed power component and reliability testing and for use to develop and optimize the rod-pinch diode load [4]. Later, Cygnus 2 was constructed and fielded at Titan-PSD for testing employing the changes and modifications that resulted from of the Cygnus 1 tests. At the time of this writing, Cygnus 2 has undergone testing of the pulsed power components up through the output of the water line where a dummy load was placed. A pulse has not yet been propagated through the water coax to the diode. This paper describes and compares the pulsed power performance of both Cygnus machines up to the output of the water line. The Cygnus testing program is a result of the cooperative effort of Titan PSD, Sandia National Laboratory, Los Alamos National Laboratory, and Bechtel Nevada.

I. General System Description

The space constraints of the underground tunnel site for the Cygnus facility require an in-line layout configuration that uses two virtually identical Cygnus 1 and 2 machines as shown in Fig. 1. The only noticeable differences between the two machines are the lengths of water coax that connect the pfl's to the IVA cells and the angling of the diode axes which are mirror images of each other.

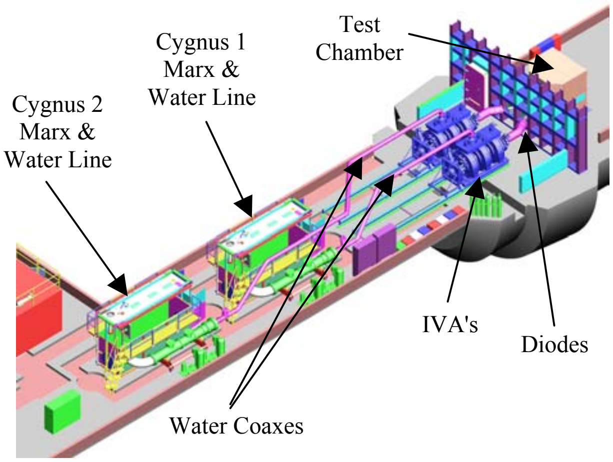

Figure 1. The planned Cygnus underground facility configuration.

Each machine is driven by a Marx generator which is shown in Fig. 2. The Marxes are synchronously fired but the charging and triggering of each is independently controlled which requires low triggering timing jitter. The pfls of each machine are identical and operated with a negative voltage applied to their inner conductors.

Each of the water lines is composed of a stepped impedance, 35 ns (1-way) pfl which discharges through a water switch into a 35 ns long 7.8-ohm output line. The stepped impedance of the pfl compensates for the diode load impedance droop that occurs during the pulse. The output line is followed by a pulse-sharpening switch that discharges this line into a second approximately 40 ns long 7.8-ohm water line followed by an oil-insulated pre-pulse suppression switch. A view of the water line components is shown in Fig. 3.

From this point, the pulse propagates through a water coax to the IVA cells and on through to the diode load. The rod pinch diode requires that the vacuum coax be driven with a positive center conductor, which is accomplished by the orientation of the IVA cells that transform the negative polarity of the water coax driving pulse. The vacuum coax must be non-emitting and hence is designed as a vacuum insulated transmission line

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14. ABSTRACT

Cygnus is a two-axis radiographic x-ray facility designed to drive rod-pinch diode loads at 2.25 MV with a spot size of about 1 mm producing 4 Rads at 1 meter. This x-ray source was developed to support the Sub-Critical Experiments Program (SCE) at the Nevada Test Site (NTS) and is distinguished from other commercially available sources by a dramatically reduced spot size for high resolution radiography, higher reliability, and compact size and modularity for greater layout flexibility to fit within the size constraints of its ultimate under-ground site location [1]. The facility is composed of two virtually identical machines referred to as Cygnus 1 and Cygnus 2 that incorporate proven pulsed power technology. Each machine employs a Marx generator, Pulse Forming Line (pfl), Water Coax Transmission Line, and Inductive Voltage Adder (IVA) that drive a high vacuum rod-pinch diode. The pfl design was originally developed for the Radiographic Integrated Test stand (RITS) [2] and the IVA cells are from the Sandia SABRE [3] accelerator. The Cygnus 1 machine was constructed and fielded at the Los Alamos National Laboratory to undergo pulsed power component and reliability testing and for use to develop and optimize the rod-pinch diode load [4]. Later, Cygnus 2 was constructed and fielded at Titan-PSD for testing employing the changes and modifications that resulted from of the Cygnus 1 tests. At the time of this writing, Cygnus 2 has undergone testing of the pulsed power components up through the output of the water line where a dummy load was placed. A pulse has not yet been propagated through the water coax to the diode. This paper describes and compares the pulsed power performance of both Cygnus machines up to the output of the water line. The Cygnus testing program is a result of the cooperative effort of Titan PSD, Sandia National Laboratory, Los Alamos National Laboratory, and Bechtel Nevada.

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(VITL). Diode performance is dependent on the risetime of the driving pulse and prepulse which necessitates the use of the pre-pulse and pulse sharpening switches in the water line section.

Figure 2. Cygnus Marx generator.

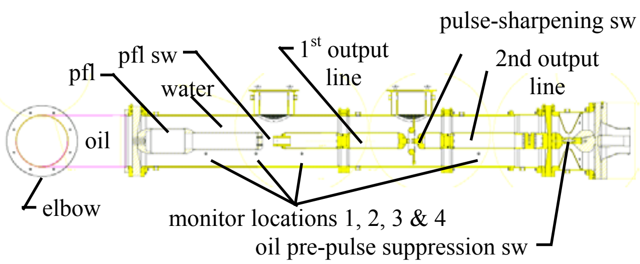

Figure 3. Cygnus water line components.

Desirable performance criteria was established for each machine to operate at the full nominal output level with no more than a single misfire in 100 shots, pulse arrival timing jitter < 25 ns (rms), and pulse amplitude reproducibility < 5% (standard deviation/average). The goal of testing each machine was to demonstrate performance within these bounds.

II. Marx Generator

The Marx circuit consists of a 33 stage, 6.06 nF oil insulated Marx that is equipped with a swing arm that connects to either a 28 ohm dummy load located in the Marx tank or the center conductor of the oil elbow that leads to the pfl. The Marx capacitor maximum charge voltage rating is 100 kV/stage but it needs to be operated at only 80 kV/stage to achieve the specified x-ray output. De-rating the Marx dc charge level to 80% significantly increases the reliability of the system. The Marx generator is a commercial design available from Titan PSD.

The use of the swing arm enables the Marx to be dc charged while the output is connected to the dummy load. Thus, in the event of a pre-fire during charging, energy is diverted into the dummy load and not applied to the diode. After full charge is achieved and just prior to firing, the swing arm is moved to connect to the oil-coax inner conductor that leads to the pfl.

The initial characterization of the Marx showed it to have a stray series inductance and resistance of 8.74 μH and 2.74 ohms respectively. These values were calculated from the ringing waveforms that resulted from firing the Marx into a short circuit placed at the downstream end of the 6.3 ns long, 46-ohm coaxial oil elbow section where the oil/water diaphragm is located. The Marx inductance includes the swing arm contribution but not the elbow's, which was subtracted from the total. The ringing waveform is shown in Fig. 4.

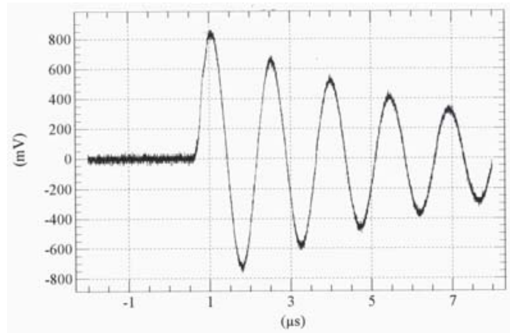

Figure 4. Marx short circuit ringing waveform.

Compared to Cygnus 1, the series Marx inductance of Cygnus 2 is several percent higher. This may be accounted for by the Marx stage buss connection spacings. The Cygnus 2 Marx was configured with its stage-to-stage busses spaced slightly further apart than those of the Cygnus 1 Marx.

The series Marx resistance of Cygnus 2 was comparable to that of Cygnus 1 as it would be expected to be.

Cygnus 1 testing determined that it was necessary to constantly flow air through the Marx switches and to operate at a pressure equivalent to 55% of the self-break voltage to achieve a pre-fire occurrence less than 1 or 2 in 200 shots. For uniform flow through all the switches, the input and output gas lines of each switch feed directly to manifolds that extend the full length of the Marx as can be seen in Fig. 2. A total flow rate of 2 ft^3/hr was determined optimal and the gas pressure used for 80 kV operation was 47 psig referenced to sea level. The use of UV illuminated switches allows operation at this low fraction of self-break while still producing good low-jitter.

A 100 kV trigger generator triggers the Marx, which is a commercial Titan PSD product model number 40230. This trigger unit drives two 50-ohm cables delivering a 100 kV pulse into an open circuit. The cables connect to the first two Marx gaps, which are resistively connected to subsequent switches.

The published trigger generator specifications are 1.3 ns risetime (10-90%) and 3 ns timing jitter (rms). Over a run of 100 shots, the Cygnus 2 trigger pulse jitter was found to be about 1.4 ns measured from t_o at the console to the trigger output. Reliability of the Cygnus 2 trigger generator was very good with only one no-fire associated with the triggering unit experienced in more than 100 shots. Cygnus 1 recently experienced a no-fire associated with the trigger generator that suggests comparable or better results since that machine has experienced only this one no-fire in more than 200 shots.

The Cygnus 2 system timing jitter was measured as 3.93 ns (rms) from t_o to the Marx output. After accounting for the trigger generator jitter, the net Marx jitter equated to 3.35 ns. This was measured over a 100 shot sequence at

a dc charge level of 80 kV per stage with normal operating parameters and firing shots at 15-minute intervals over a four day period.

No pre-fires occurred during the Cygnus 2, 100 shot run. Cygnus 1 has had similar results.

III. Water Line Switch Performance

The water line assembly is shown in Fig. 3. The water line diagnostics consist of a V-dot and B-dot monitor placed at each of four locations along the length of the line. The first location is midway down the pfl. The second is just upstream of the pfl switch. The third is just beyond the pfl switch located at the first output line. The fourth location is approximately midway down the second output line upstream of the oil switch.

The pfl represents a capacitance of about 4.5 nF and is charged in about 430 ns to switchout. At nominal full operating voltage, the pfl voltage reaches about 2.4 MV to 2.5 MV.

A pfl switch gap of 3.625 inches was used in the Cygnus 2 tests while a 3.75-inch gap was used in Cygnus 1 while operating at the nominal full voltage. This accounts for the slightly delayed closure of the Cygnus 1 switch relative to that of Cygnus 2 as shown in Fig. 5 where the two waveforms are normalized and overlaid. The pulse out of the pfl switch onto the output line is shown in Fig. 6 and rises in about 18 ns (10-90%) consistent with a single channel arc with an inductance of about 15 nH/cm. The peak voltage on the output line is about 1.2 MV as would be expected from the impedances of the lines.

The water pulse-sharpening switch operated at nominal full operating voltage using a gap of 0.25 inches in Cygnus 1 and 0.3125 inches in Cygnus 2. The oil pre-pulse switch operated with a gap 0.125 inches in both machines.

Figure 7 shows the normalized waveforms of the pulse downstream of the prepulse switch for both Cygnus 1 and 2. The voltage at this point is about 900 kV but reaches about 1.35 MV due to the reflection caused by the momentary hold-off of the oil switch.

While Cygnus 1 has been operating into the water coax and diode load for some time, Cygnus 2 has used a dummy load placed immediately downstream of the oil switch. The value of this liquid resistor load was set at 5.8 ohms to be equivalent to the initial water coax impedance. The use of this dummy load presumably accounts in the faster fall time of the Cygnus 2 output line waveform.

During a 100 shot run of Cygnus 2 operating at nominal full voltage with approximately 2.4-2.5 MV on the pfl, the rms jitter of the pfl water switch was measured as about 9.2 ns with a total spread of 59 ns. The total spread of the pfl switch out voltage was about 6.4% of the mean value. This compares with the Cygnus 1 results where the closure timing total spread was about 50 ns and pfl switchout voltage total spread was 6%.

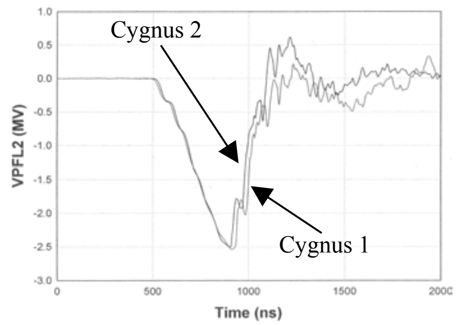

Figure 5. Overlay of Cygnus 1 and 2 pfl voltage waveforms measured at monitor location 2.

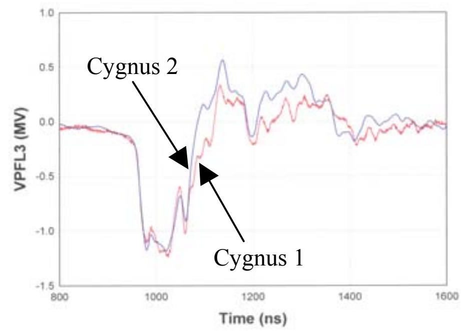

Figure 6. Overlay of Cygnus 1 and 2 waveform measured at monitor location 3 (downstream of pfl switch).

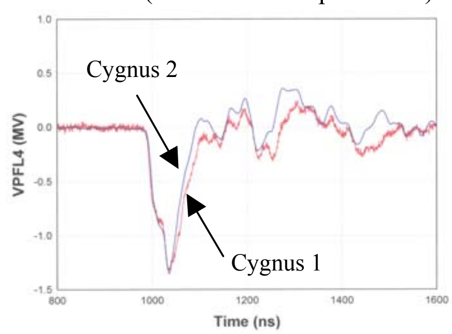

Figure 7. Overlay of Cygnus 1 and 2 waveforms measured at monitor location 4 (downstream of pulse-sharpening switch).

The closure jitter contribution from the pulse-sharpening switch was negligible because the measured throughput jitter of its output was slightly less than the throughput jitter of the pfl switch output measured over the 100-shot run. Without any jitter in the sharpening switch, both throughput jitter measurements would have been the same. However, as sometimes happens, delayed pfl switch closure can produce a faster rising output that is compensated for by the downstream switch closing earlier thus reducing the overall throughput jitter.

IV. PFL Diaphragm Breakdowns

Because of the desire to compensate for the diode impedance droop, Cygnus uses a stepped impedance pfl. This original design incorporated a lower upstream impedance of 6 ohms (14 ns 1-way) followed by a 9.2 ohm section (19 ns 1-way) and has been used successfully in well over 100 shots in Cygnus 1. With such a pfl, the peak voltage achieved for nominal full output operation was about 2.7 MV.

Early in the testing phase of Cygnus 1, a straight RITS-like 7.8-ohm impedance pfl was briefly used and resulted in a tracking of the Polycarbonate oil/water diaphragm at 110% of nominal full operating voltage where the pfl voltage reached 3 MV. A streamer was evidently launched from the edge of the inner conductor and attached to and propagated along the electrically weaker diaphragm surface.

Profiles of these straight and stepped pfl's with their respective equi-potentials plotted are shown in Figs. 8 and 9 with the peak edge fields determined for 2.7 MV on the pfl. The straight pfl inner actually has lower fields at both its negative inner and positive outer edges that are adjacent to the surface of the diaphragm than the stepped inner has. However, streamers launched from the edge of the straight inner conductor would be directed along the field lines towards the electrically weaker surface of the plastic barrier resulting in a surface track. In the case of the stepped inner, a streamer would more likely follow a path along the field lines into the electrically stronger open water where it would likely dissipate and not close to the outer coax wall.

In both cases, the breakdown fractions for either the positive outer or negative inner edges are low; <45% for the straight conductor case and <60% for the stepped case.

Peak field levels are equivalent on the plastic interface for both inner conductor shapes and are 235 kV/cm.

It was speculated that an important figure of merit was to distance the enhanced edge of the inner conductor as far from the plastic interface surface as possible and to consider a lower average impedance pfl that could be charged to a somewhat lower voltage without reducing the x-ray out-put dose. A detailed transmission line code simulation of the Cygnus circuit confirmed that a lower impedance pfl would result in no degradation of x-ray output at a given Marx charge voltage.

The PFL inner conductor profile shown in Fig. 10 with the equi-potentials plotted was chosen. This design has an upstream section of 4.8 ohms (14 ns 1-way) with the remainder 7.3 ohms (19 ns 1-way). With this lower average impedance, the peak voltage on the PFL to achieve full output is reduced to about 2.45 MV. In addition, the plastic interface surface shape shown was the result of optimally reducing the fields to make them as uniform as possible along this surface.

The negative inner conductor breakdown fraction is 56% and the positive outer is at about 70% at nominal full voltage output at 2.45 MV on the pfl.

This modified PFL inner profile was successfully used in Cygnus 2 for over 150 shots so far. Cygnus 1 also had success for about 100 shots and confirmed that diode and dose outputs are similar to previous results from the original stepped pfl impedance. Recently, however, Cygnus 1 experienced a track of the interface even though the fields everywhere would be expected to be safe.

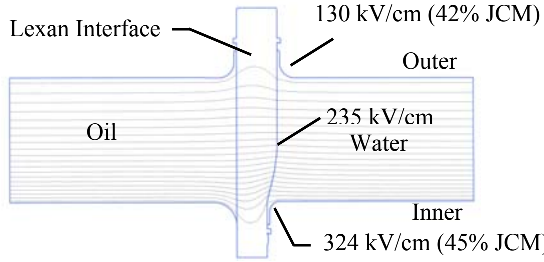

Figure 8. Straight pfl inner with original diaphragm contour.

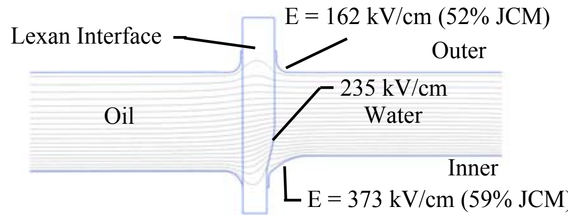

Figure 9. Original stepped pfl inner and diaphragm contours.

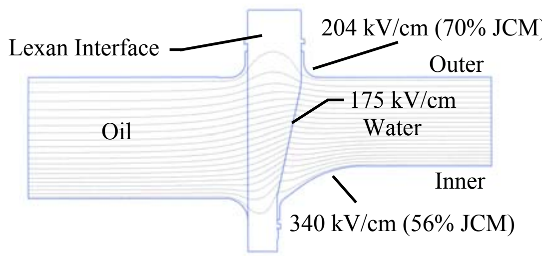

Figure 10. Most recently used pfl inner and diaphragm contours.

A preliminary examination of the diaphragm suggests that the failure was anomalous and possibly caused by debris laying on the outer conductor edge or a defect in the plastic interface. It appears that the initiation of the arc may have been on the plastic surface which subsequently closed to the inner and outer conductor. Thus, the design is assumed to be satisfactory and is about as good as it can be for the given diameter of the water line in view of the uniform field distribution.

V. Conclusion

The Cygnus 1 and Cygnus 2 machines share a common design but were constructed and tested independently. Tests have demonstrated that their pulsed power performance is similar and their reliability adequate to be fielded at their designated underground facility location.

References

1. D. Weidenheimer et al., Proc. 13th IEEE Pulsed Power Conf., 17-22 June 2001, pp. 591-595.
2. I.D. Smith et al., IEEE Trans. On Plasma Science, Vol. 28, No. 5, October 2000.
3. J.P. Corley et al., Proc. of 8th IEEE Pulsed Power Conf., 1991, pp. 920-923.
4. J.R. Smith et al, Proc. 14th International Conference on High Power Particle Beams, 23-28 June 2002, pp. 135-138.